New (and Old) Perspectives on Higgs Physics[1]

John F. Gunion

Department of Physics, University of California, Davis, CA 95616

Abstract. Old and new ideas regarding Higgs physics are reviewed. We first summarize the quadratic divergence / hierarchy problem which strongly suggests that the SM Higgs sector will be supplemented by new physics at high scales. We next consider means for delaying the hierarchy problem of the SM Higgs sector to unexpectedly high scales. We then outline the properties of the most ideal Higgs boson. The main advantages of a supersymmetric solution to the high scale problems are summarized and the reasons for preferring the next-to-minimal supersymmetric model over the minimal supersymmetric model in order to achieve an ideal Higgs are emphasized. This leads us to the strongly motivated scenario in which there is a Higgs h with SM-like WW, ZZ couplings and $m_h \sim 100$ GeV that decays via $h \to aa$ with $m_a < 2m_b$, where $m_a > 2m_\tau$ is preferred, implying $a \to \tau^+\tau^-$. The means for detecting an $h \to aa \to 4\tau$ signal are then discussed. Some final cautionary and concluding remarks are given.

Keywords: Document processing, Class file writing, LaTeX 2_ε
PACS: 12.60.Fr,12.60.Jv,12.60.-i,14.80.Cp,11.30.Pb

INTRODUCTION

The number one issue in Higgs physics is the solution of the hierarchy / fine-tuning problems that arise in the Standard Model and Higgs sector extensions thereof from quadratically divergent one-loop corrections to the Higgs mass. In fact, this "quadratic divergence fine-tuning" is only one of three fine-tunings that we will discuss. The second kind of fine-tuning is that sometimes called "electroweak fine-tuning"; it is the fine-tuning associated with getting the value of m_Z correct starting from GUT-scale parameters of some model that already embodies a solution to the quadratic fine-tuning problem. A third type of fine-tuning will emerge in the context of the next-to-minimal supersymmetric model solution to avoiding electroweak fine-tuning.

Were it not for the quadratic divergence fine-tuning problem, there is nothing to forbid the SM from being valid all the way up to the Planck scale. The two basic theoretical constraints on $m_{h_{SM}}$ as a function of the scale Λ at which new physics enters are:

- the Higgs self coupling should not blow up below scale Λ — this leads to an upper bound on $m_{h_{SM}}$ as a function of Λ.
- the Higgs potential should not develop a new minimum at large values of the scalar field of order Λ — this leads to a lower bound on $m_{h_{SM}}$ as a function of Λ.

The SM remains consistent with these two constraints all the way up to $\Lambda \sim M_P$ if $130 \lesssim m_{h_{SM}} \lesssim 180$ GeV. This is shown in Fig. 1. However, it is generally believed that

---

[1] This writeup is based on a presentation at Scadron 70, "Workshop on Scalar Mesons and Related Topics", Lisbon, Portugal, February, 2008.
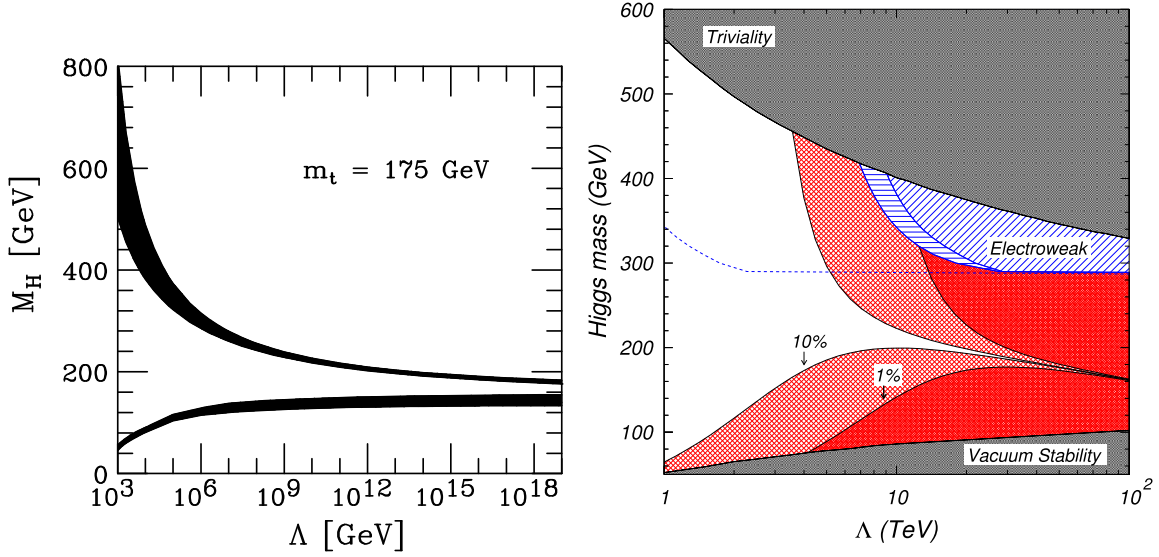
FIGURE 1. Left: Triviality and global minimum constraints on $m_{h_{SM}}$ vs. Λ from Ref. [1]. Right: Fine-tuning constraints on Λ, from Ref. [2].

the SM cannot be the full theory all the way up to M_P due to quadratic divergence of loop corrections to the Higgs mass. Because of this divergence, a light Higgs is not "natural" in the SM context given the large "hierarchy" between the 100 GeV and M_P scales. Assuming that the SM is valid up to some large scale Λ, to obtain the low Higgs mass favored by data (and required by WW scattering perturbativity) requires an enormous cancellation between top loop corrections (as well as W, Z and h_{SM} loops) and the bare Higgs mass of the Lagrangian. At one-loop, assuming cutoff scale Λ,

$$m_{h_{SM}}^2 = m_0^2 + \frac{3}{16\pi^2}(2m_W^2 + m_Z^2 + m_{h_{SM}}^2 - 4m_t^2)\Lambda^2 \tag{1}$$

where $m_0^2 = 2\lambda v_{SM}^2$ with $v_{SM} \sim 174$ GeV. ($V \ni \frac{1}{2}\lambda^2[(\Phi^\dagger\Phi)^2 - v_{SM}^2(\Phi^\dagger\Phi)]$ and $\langle\Phi\rangle = v_{SM}$.) Assuming no particular connection between the contributions, we must fine tune m_0^2 to cancel the Λ^2 term with something like a precision of one part in 10^{32} if $\Lambda = M_P$. Further, this requires that the Higgs self-coupling strength, λ, must be very large and non-perturbative. Keeping only the m_t term with $\Lambda \to \Lambda_t$, one measure of fine-tuning is:

$$F_t(m_{h_{SM}}) = \left|\frac{\partial\delta m_{h_{SM}}^2}{\partial\Lambda_t^2}\frac{\Lambda_t^2}{m_{h_{SM}}^2}\right| = \frac{3}{4\pi^2}\frac{m_t^2}{v_{SM}^2}\frac{\Lambda_t^2}{m_{h_{SM}}^2} \equiv K\frac{\Lambda_t^2}{m_{h_{SM}}^2}. \tag{2}$$

Given a maximum acceptable F_t, new physics must enter at or below the scale

$$\Lambda_t \lesssim \frac{2\pi v_{SM}}{\sqrt{3}m_t}m_{h_{SM}}F_t^{1/2} \sim 400\,\text{GeV}\left(\frac{m_{h_{SM}}}{115\,\text{GeV}}\right)F_t^{1/2}. \tag{3}$$

$F_t > 10$, corresponding to fine-tuning parameters with a precision of better than 10%, is deemed problematical. For $m_{h_{SM}} \sim 100$ GeV, as preferred by precision electroweak data, this implies new physics somewhat below 1 TeV, in principle well within LHC reach.

OPTIONS FOR DELAYING NEW PHYSICS

Given that by definition new physics enters at scale Λ, it is generically interesting to understand how the quadratic divergence fine-tuning problem can be delayed to Λ values substantially above 1 TeV, thereby making LHC new-physics signals more difficult to detect. Two possible ways are the following.

1. $m_{h_{\text{SM}}}$ could obey the "Veltman" condition [3] (see also [4] and [5]),

$$m_{h_{\text{SM}}}^2 = 4m_t^2 - 2m_W^2 - m_Z^2 \sim (317 \text{ GeV})^2 ,\qquad (4)$$

   for which the coefficient of Λ^2 in Eq. (1) vanishes. However, it turns out that at higher loop order, one must carefully coordinate the value of $m_{h_{\text{SM}}}$ with the value of Λ [2]. Just as we do not want to have a fine-tuned cancellation of the two terms in Eq. (4), we also do not want to insist on too fine-tuned a choice for $m_{h_{\text{SM}}}$ (in the SM, there is no symmetry that predicts any particular value). The right-hand plot of Fig. 1 shows the result after taking this into account. The upper bound for Λ at which new physics must enter is largest for $m_{h_{\text{SM}}} \sim 200$ GeV where the SM fine-tuning would be 10% if $\Lambda \sim 30$ TeV. At this point, one would have to introduce some kind of new physics. However, we already know that there is a big problem with this approach — the latest m_t and m_W values when combined with LEP precision electroweak data require $m_{h_{\text{SM}}} < 160$ GeV at 95% CL.

2. An alternative approach to delaying quadratic divergence fine-tuning is to employ the multi-doublet model of [6]. In this model, the ZZ coupling is shared among (perhaps many) Higgs mass eigenstates because the SM vev is shared among the corresponding Higgs fields. A bit of care in setting the scenario up is needed to avoid seeing other Higgs while at the same time satisfying the precision EW constraint:

$$\sum_i \frac{v_i^2}{v_{SM}^2} \ln m_{h_i} \lesssim \ln (160 \text{ GeV}) ,\qquad (5)$$

   where $\langle \Phi_j \rangle \equiv v_j$ and $\sum_j v_j^2 = v_{SM}^2 \sim (175 \text{ GeV})^2$. If you don't want LEP to have seen any sign of a Higgs boson, the PEW constraint can still be satisfied even if all the Higgs decay in SM fashion, so long as the eigenstates are not too much below 100 GeV and not degenerate. But, of course, with enough h_j eigenstates, Higgs decays will not be SM-like given the proliferation of $h_j \to h_i h_i$ and $h_j \to a_i a_i$ decays. The combination of such decays and weakened production rates for the individual Higgs bosons would make Higgs detection very challenging at the LHC and require a high-luminosity linear collider. Returning to the quadratic divergence issue, we note that in the simplest case where all h_i fields have the same top-quark Yukawa, λ_t in $\mathscr{L} = \lambda_t \bar{t} h_i t$, each h_i has its top-quark-loop mass correction scaled by $f_i^2 \equiv \frac{v_i^2}{v_{SM}^2}$ and one gets a significantly reduced F_t for each h_i:

$$F_t^i = f_i^2 F_t(m_i) = K f_i^2 \frac{\Lambda_t^2}{m_i^2} .\qquad (6)$$

TABLE 1. LEP m_H Limits for an H with SM-like ZZ coupling, but varying decays.

Mode	SM modes	2τ or $2b$ only	$2j$	$WW^* + ZZ^*$	$\gamma\gamma$	$E\!\!\!/$	$4e, 4\mu, 4\gamma$
Limit (GeV)	114.4	115	113	100.7	117	114	114?

Mode	$4b$	4τ	any (e.g. $4j$)	$2f + E\!\!\!/$			
Limit (GeV)	110	86	82	90?			

Thus, multiple mixed Higgs allow a much larger Λ_t for a given maximum acceptable common F_t^i. A model with 4 doublets can have $F_t^i < 10$ for Λ_t up to 5 TeV.

One good feature of delaying new physics is that large Λ_t implies that significant corrections to low-E phenomenology from Λ_t-scale physics (*e.g.* FCNC) are less likely. However, in the end, there is always going to be a Λ or Λ_t for which quadratic divergence fine-tuning becomes unacceptable. Ultimately we will need new physics. So, why not have it right away (*i.e.* at $\Lambda \lesssim 1$ TeV) and avoid the above somewhat ad hoc games. This is the approach of supersymmetry, which (unlike Little Higgs or UED or ....) solves the hierarchy problem once and for all, *i.e.* there is no need for an unspecified ultraviolet completion of the theory. We will return to supersymmetry momentarily.

CRITERIA FOR AN IDEAL HIGGS THEORY

Theory and experiment have led us to a set of criteria for an ideal Higgs theory. We list these below.

- It should allow for a light Higgs boson without quadratic divergence fine-tuning.
- It should predict a Higgs with SM couplings to WW, ZZ and with mass in the range preferred by precision electroweak data. The LEPEWWG plot from winter 2008 is shown in Fig. 2. At 95% CL, $m_{h_{SM}} < 160$ GeV and the $\Delta\chi^2$ minimum is between 80 GeV and 100 GeV.
- Thus, in an ideal model, the Higgs should have mass no larger than 100 GeV. But, at the same time, one must avoid the LEP limits on such a light Higgs. One generic possibility is for the Higgs decays to be non-SM-like. The limits on various Higgs decay modes from LEP are given in Table 1, taken from Ref. [7]. From this table, we see that to have $m_H \leq 100$ GeV requires that the Higgs decays to one of the final three modes or something even more exotic.
- Perhaps the Higgs properties should be such as to predict the 2.3σ excess at $M_{b\bar{b}} \sim 98$ GeV seen in the $Z + b\bar{b}$ final state — see Fig. 3. For consistency with the observed excess, the $e^+e^- \to ZH \to Zb\bar{b}$ rate should be about one-tenth the SM value. There are two obvious ways to achieve this: (1) one could have $B(H \to b\bar{b}) \sim 0.1 B(H \to b\bar{b})_{SM}$ and $g_{ZZH}^2 \sim g_{ZZh_{SM}}^2$; or (2) $B(H \to b\bar{b})$ could be SM-like but $g_{ZZH}^2 \sim 0.1 g_{ZZh_{SM}}^2$.
  Regarding (1), almost any additional decay channel will severely suppress the $b\bar{b}$ branching ratio. A Higgs of mass 100 GeV has a decay width into Standard Model particles that is only 2.6 MeV, or about 10^{-5} of its mass. This implies that it doesn't
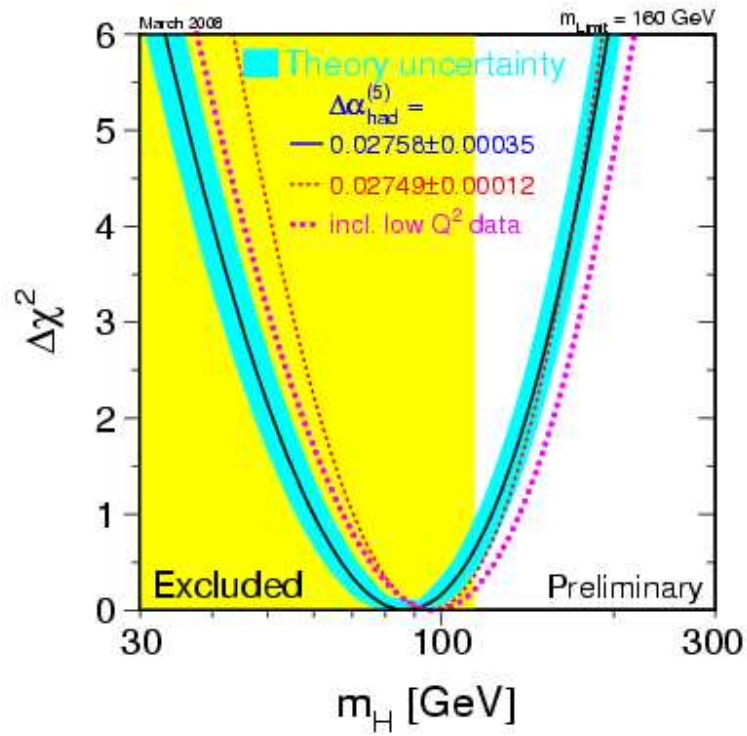
FIGURE 2. The "blue-band" plot showing the preferred Higgs mass range as determined using precision electroweak data and measured top and W boson masses.
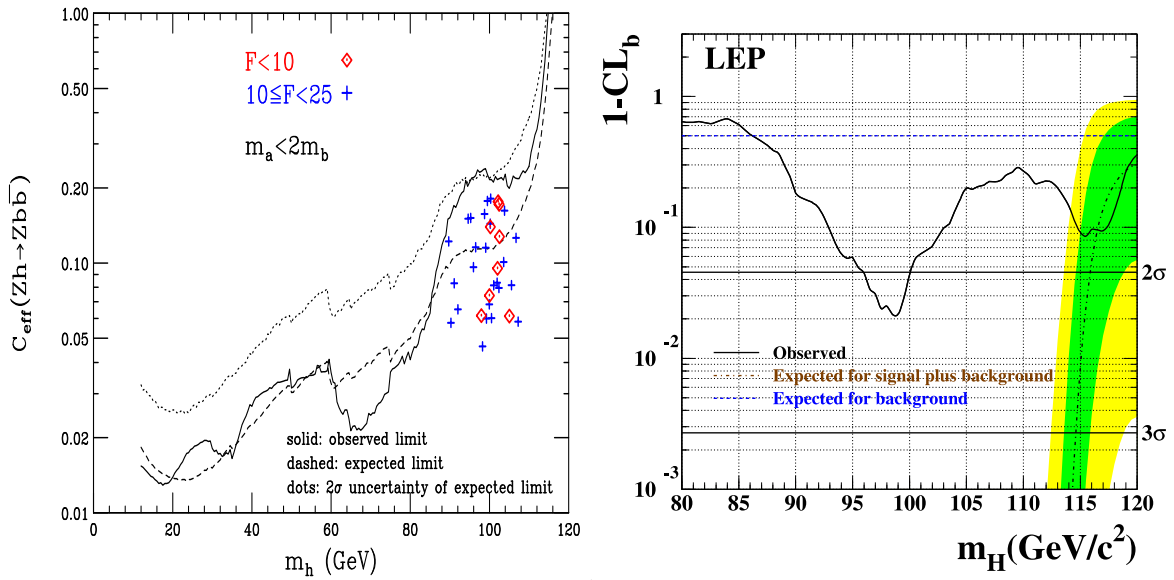

FIGURE 3. LEP plots for the $Zb\bar{b}$ final state from the LEP Higgs Working Group.

take a large Higgs coupling to some new particles for the decay width to these new particles to dominate over the decay width to SM particles — see [8], [9], and [10] (as reviewed in [7]). For example, compare the decay width for $h \rightarrow b\overline{b}$ to that for $h \rightarrow aa$, where a is a light pseudoscalar Higgs boson. Writing $\mathscr{L} \ni g_{haa} haa$ with $g_{haa} \equiv c \frac{g m_h^2}{2 m_W}$ and ignoring phase space suppression, we find

$$\frac{\Gamma(h \rightarrow aa)}{\Gamma(h \rightarrow b\overline{b})} \sim 310 c^2 \left(\frac{m_h}{100 \text{ GeV}} \right)^2. \tag{7}$$

This expression includes QCD corrections to the $b\overline{b}$ width as given in HDECAY which decrease the leading order $\Gamma(h \rightarrow b\overline{b})$ by about 50%. The decay widths are comparable for $c \sim 0.057$ when $m_h = 100$ GeV. Values of c at this level or substantially higher (even $c = 1$ is possible) are generic in BSM models containing an extended Higgs sector.

Regarding possibility (2), let us return to the scenario of [6] in which the ZZ coupling is shared among many Higgs mass eigenstates. To explain the 2.3σ excess, there should be a Higgs field having vev squared of order $0.1 \times v_{SM}^2$ and corresponding eigenstate with mass ~ 100 GeV. (This simple scenario assumes no Higgs mixing — incorporation of mixing is straightforward.) An interesting special case is to construct a 2HDM with $m_{h^0} = 98$ GeV and $g_{ZZh^0}^2 = 0.1 g_{ZZh_{SM}}^2$ and with $m_{H^0} = 116$ GeV (the other LEP excess) and $g_{ZZH^0}^2 \sim 0.9 g_{ZZh_{SM}}^2$ (see, for example, [11]). As discussed earlier, multiple Higgs games are also "useful" in that they can delay the quadratic divergence fine-tuning problem to higher Λ.

WHY SUPERSYMMETRY

Ultimately, however, we must solve the quadratic divergence problem. There are many reasons why supersymmetry is regarded as the leading candidate for a theory beyond the SM that accomplishes this. Let us review them very briefly. (a) SUSY is mathematically intriguing. (b) SUSY is naturally incorporated in string theory. (c) Elementary scalar fields have a natural place in SUSY, and so there are candidates for the spin-0 fields needed for electroweak symmetry breaking and Higgs bosons. (d) SUSY cures the naturalness / hierarchy problem (quadratic divergences are largely canceled) in a particularly simple way. And, it does so without electroweak fine-tuning (see definition below) provided the SUSY breaking scale is $\lesssim 500$ GeV. For example, the top quark loop (which comes with a minus sign) is canceled by the loops of the spin-0 partners called "stops" (which loops enter with a plus sign). Thus, Λ_t^2 is effectively replaced by $\overline{m}_{\tilde{t}}^2 \equiv m_{\tilde{t}_1} m_{\tilde{t}_2}$.

Overall, the most minimal version of SUSY, the MSSM comes close to being very nice. If we assume that all sparticles reside at the $\mathscr{O}(1 \text{ TeV})$ scale and that μ is also $\mathscr{O}(1 \text{ TeV})$, then, the MSSM has two particularly wonderful properties. First, the MSSM sparticle content plus two-doublet Higgs sector leads to gauge coupling unification at $M_U \sim few \times 10^{16}$ GeV, close to M_P — see Fig. 4. High-scale unification correlates well with the attractive idea of gravity-mediated SUSY breaking. Second, starting with universal soft-SUSY-breaking masses-squared at M_U, the RGE's predict that the top quark Yukawa coupling will drive one of the soft-SUSY-breaking Higgs masses-squared
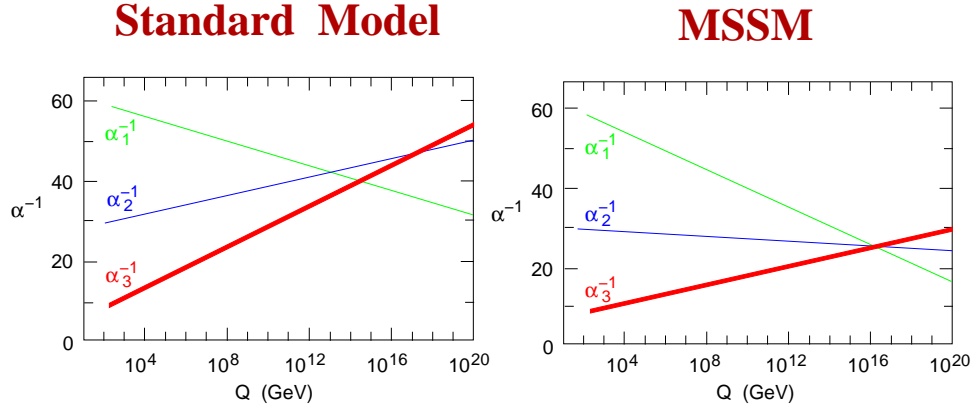
Standard Model

MSSM

FIGURE 4. Unification of couplings constants ($\alpha_i = g_i^2/(4\pi)$) in the minimal supersymmetric model (MSSM) as compared to failure without supersymmetry.
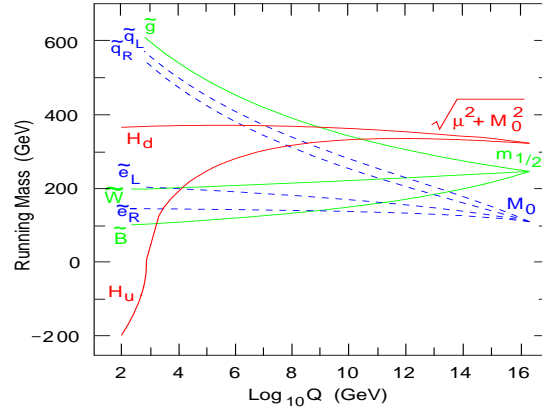

FIGURE 5. Evolution of the (soft) SUSY-breaking masses or masses-squared, showing how $m_{H_u}^2$ is driven < 0 at low $Q \sim \mathcal{O}(m_Z)$.

($m_{H_u}^2$) negative at a scale of order $Q \sim m_Z$, thereby automatically generating electroweak symmetry breaking ($\langle H_u \rangle = h_u, \langle H_d \rangle = h_d$, where H_u and H_d are the two scalar Higgs fields of the MSSM) — see Fig. 5. However, as we shall discuss, fine-tuning of the GUT-scale parameters may be required in order to obtain the correct value of m_Z unless, for example, the stop masses are no larger than $2m_t$ or so.

MSSM PROBLEMS

However, the MSSM is suspect because of two critical problems.

- **The μ parameter problem:** In $W \ni \mu \widehat{H}_u \widehat{H}_d$,[2] μ is dimensionful, unlike all other superpotential parameters. Phenomenologically, it must be $\mathcal{O}(1 \text{ TeV})$ (as required for proper EWSB and in order that the chargino mass be heavier than the lower bounds from LEP and Tevatron experiments). However, in the MSSM context the most natural values are either $\mathcal{O}(M_U, M_P)$ or 0.

- **LEP limits and Electroweak Fine-tuning:** Since the lightest Higgs, h, of the (CP conserving) MSSM has SM-like coupling *and* decays, the LEP limit of $m_h > 114.4$ GeV applies for most of MSSM parameter space. Such a h is only possible for special MSSM parameter choices, for example large $\tan\beta = v_u/v_d$ and large stop masses (roughly $\sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}} \gtrsim 900$ GeV) or large stop mixing. To quantify the problem we define

$$F = \text{Max}_p \left| \frac{p}{m_Z} \frac{\partial m_Z}{\partial p} \right|, \tag{8}$$

  where $p \in \left\{ M_{1,2,3}, m_Q^2, m_U^2, m_D^2, m_{H_u}^2, m_{H_d}^2, \mu, A_t, B\mu, \ldots \right\}$ (all at M_U). These p's are the GUT-scale parameters that determine all the m_Z-scale SUSY parameters, and these in turn determine v_{SM}^2 to which m_Z^2 is proportional. For example, $F > 20$ means worse than 5% fine-tuning of the GUT-scale parameters is required to get the right value of m_Z, a level generally regarded as unacceptable. Thus, an important question is what is the smallest F that can be achieved while keeping $m_h > 114$ GeV. The answer is (see, in particular, [12, 13]): (a) For most of parameter space, $F > 100$ or so; (b) For a part of parameter space with large mixing between the stops, F can be reduced to 16 at best (6% fine-tuning), but this part of parameter space has many other peculiarities. An ideal model would have $F \lesssim 5$, which corresponds to absence of any significant electroweak fine-tuning.

THE NMSSM

Both problems are nicely solved by the next-to-minimal supersymmetric model (NMSSM) in which a single extra singlet superfield is added to the MSSM. The new superpotential and associated soft-SUSY-breaking terms are

$$W \ni \lambda \widehat{S} \widehat{H}_u \widehat{H}_d + \tfrac{1}{3} \kappa \widehat{S}^3, \quad V \ni \lambda A_\lambda S H_u H_d + \tfrac{1}{3} \kappa A_\kappa S^3. \tag{9}$$

The explicit $\mu \widehat{H}_u \widehat{H}_d$ term found in the MSSM superpotential is removed. Instead, μ is automatically generated by $\langle S \rangle \neq 0$ leading to $\mu_{eff} \widehat{H}_u \widehat{H}_d$ with $\mu_{eff} = \lambda \langle S \rangle$. The only requirement is that $\langle S \rangle$ not be too small or too large. This is automatic if there are no dimensionful couplings in the superpotential since $\langle S \rangle$ is then of order the SUSY-breaking scale, which will be of order a TeV or below.

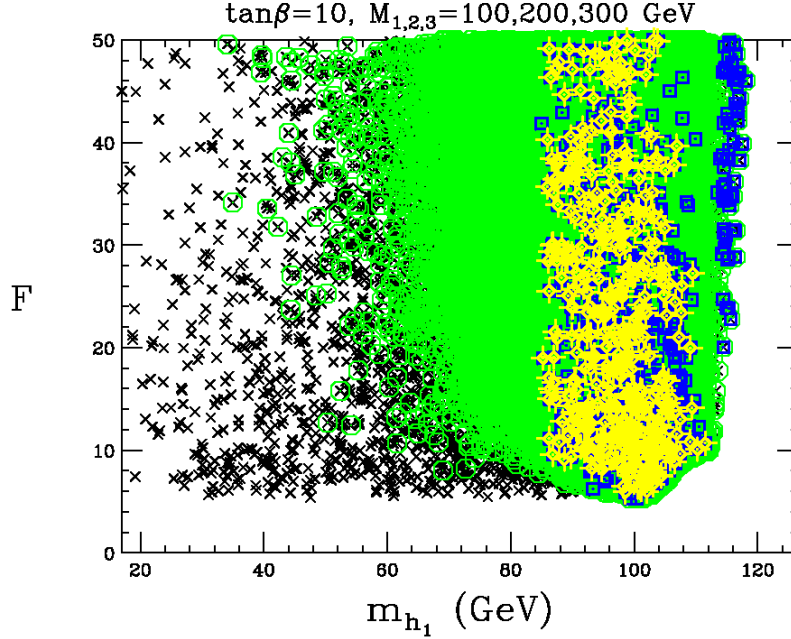[2] Hatted (unhatted) capital letters denote superfields (scalar superfield components).

FIGURE 6. F vs. m_{h_1} for $M_{1,2,3} = 100, 200, 300\,\text{GeV}$ and $\tan\beta = 10$. Small $\times$ points have no constraints other than the requirement that they correspond to a global and local minimum, do not have a Landau pole before M_U and have a neutralino LSP. The O points are those which survive after stop and chargino mass limits are imposed, but no Higgs limits. The square points pass all LEP *single channel*, in particular $Z + 2b$ and $Z + 4b$, Higgs limits. The large yellow fancy crosses are those left after requiring $m_{a_1} < 2m_b$, so that LEP limits on $Z + b's$, where $b's = 2b + 4b$, are not violated.

Electroweak fine-tuning and its implications for the NMSSM have been studied in [12, 13, 14, 15, 16, 17, 18] and reviewed in [19, 7]. Electroweak fine-tuning can be absent since the sparticles, especially the stops, can be light without predicting a light Higgs boson with properties such that it has already been ruled out by LEP, a point we return to shortly. A plot of F as a function of the mass of the lightest CP-even Higgs, m_{h_1}, appears in Fig. 6. The electroweak fine-tuning parameter has a minimum of order $F \sim 5$ (which arises for stop masses of order 350 GeV) for $m_{h_1} \sim 100$ GeV, even without placing any experimental constraints on the model (the $\times$ points). This is perfect for precision electroweak constraints because the h_1 has very SM-like WW, ZZ couplings and an ideal mass. However, most of the $\times$ points are such that the h_1 is excluded by LEP. Only the fancy-yellow-cross points pass all LEP Higgs constraints, but there are many of these with $F \sim 5$. These points are such that $m_{h_1} \sim 100$ GeV *and* the h_1 avoids LEP Higgs limits by virtue of $B(h_1 \to a_1 a_1) > 0.75$ with $m_{a_1} < 2m_b$. (Here, a_1 is the lightest of the two CP-odd Higgs bosons of the NMSSM.) In the $h_1 \to a_1 a_1 \to 4\tau$ channel, the LEP lower limit is $m_{h_1} > 87$ GeV. In the $h_1 \to a_1 a_1 \to 4j$ channel, the LEP lower limit is $m_{h_1} > 82$ GeV — see Table 1.

Further, there is an intriguing coincidence. For the many points with $B(h_1 \to a_1 a_1) >$

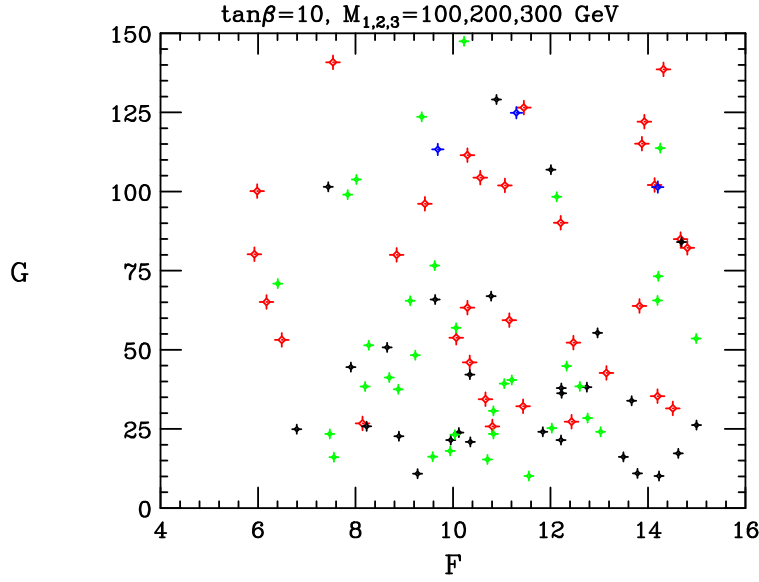**FIGURE 7.** G vs. F for $M_{1,2,3} = 100, 200, 300$ GeV and $\tan\beta = 10$ for points with $F < 15$ having $m_{a_1} < 2m_b$ and large enough $B(h_1 \to a_1 a_1)$ to escape LEP limits. The color coding is: blue $= m_{a_1} < 2m_\tau$; red $= 2m_\tau < m_{a_1} < 7.5$ GeV; green $= 7.5$ GeV $< m_{a_1} < 8.8$ GeV; and black $= 8.8$ GeV $< m_{a_1} < 9.2$ GeV.

0.85, then $B(h_1 \to b\overline{b}) \sim 0.1$ and the 2.3σ LEP excess near $m_{b\overline{b}} \sim 98$ GeV in $e^+e^- \to Z + b's$ is perfectly explained. There are a significant number of such points in NMSSM parameter space. For these points, the h_1 satisfies all the properties listed earlier for an "ideal" Higgs. Further, for these points the GUT-scale SUSY-breaking parameters (such as the Higgs soft masses-squared, the A_κ and A_λ soft-SUSY-breaking parameters, and the A_t stop mixing parameter) are particularly appealing being generically of the 'no-scale' variety. That is, for the lowest F points we are talking about, almost all the soft-SUSY-breaking parameters are small at the GUT scale. This is a particularly attractive possibility in the string theory context.

There is one remaining issue for these NMSSM scenarios. We must ask whether a light a_1 with the right properties is natural, or does this require fine-tuning of the GUT-scale parameters? This is the topic of [16]. The answer is that these scenarios can be very natural. First, we note that the NMSSM has a $U(1)_R$ symmetry obtained when A_κ and A_λ are set to zero. If this limit is applied at scale m_Z, then, $m_{a_1} = 0$. But, it turns out that then $B(h_1 \to a_1 a_1) \lesssim 0.3$, which does not allow escape from the LEP limit. However, the much more natural idea is to impose the $U(1)_R$ symmetry at the GUT scale. Then, the renormalization group often generates exactly the values for A_κ and A_λ needed to obtain a light a_1 with large $B(h_1 \to a_1 a_1)$.

Quantitatively, we measure the tuning needed to get small m_{a_1} and large $B(h_1 \to a_1 a_1)$ using a quantity called G (the "light-a_1 tuning measure"). We want small G as well as small F for scenarios such that the light Higgs is consistent with LEP limits. Fig. 7 shows that it is possible to get small G and small F simultaneously for phenomenologically acceptable points if $m_{a_1} > 2m_\tau$ (but still below $2m_b$). A phenomenologically important quantity is $\cos\theta_A$, the coefficient of the MSSM-like doublet Higgs component, A_{MSSM},
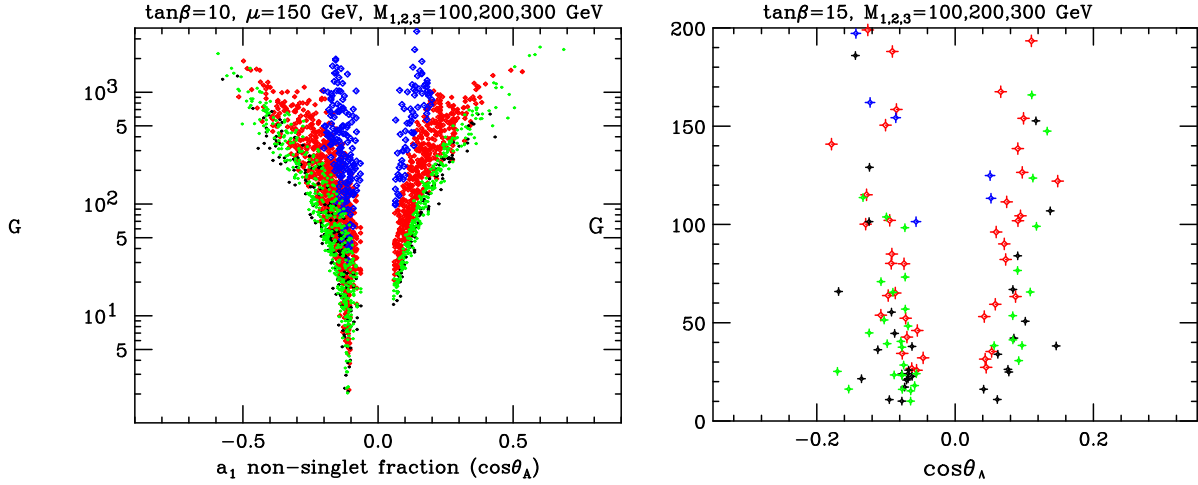
FIGURE 8. G vs. $\cos\theta_A$ for $M_{1,2,3} = 100, 200, 300\,\text{GeV}$ and $\tan\beta = 10$ from $\mu_{\text{eff}} = 150\,\text{GeV}$ scan (left) and for points with $F < 15$ (right) having $m_{a_1} < 2m_b$ and large enough $B(h_1 \to a_1 a_1)$ to escape LEP limits. The color coding is: blue = $m_{a_1} < 2m_\tau$; red = $2m_\tau < m_{a_1} < 7.5\,\text{GeV}$; green = $7.5\,\text{GeV} < m_{a_1} < 8.8\,\text{GeV}$; and black = $8.8\,\text{GeV} < m_{a_1} < 9.2\,\text{GeV}$.

of the a_1 defined by

$$a_1 = \cos\theta_A A_{MSSM} + \sin\theta_A A_S \tag{10}$$

where A_S is the singlet pseudoscalar field. The value of G as a function of $\cos\theta_A$ for various m_{a_1} bins is shown in Fig. 8 for points consistent with LEP bounds. Really small G occurs for $m_{a_1} > 7.5\,\text{GeV}$ and $\cos\theta_A \sim -0.1$. Also note that there is a lower bound on $|\cos\theta_A|$. This lower bound arises because $B(h_1 \to a_1 a_1)$ falls below 0.75 for too small $|\cos\theta_A|$. For the preferred $\cos\theta_A \sim -0.1$ values, the a_1 is mainly singlet and its coupling to $b\bar{b}$, being proportional to $\cos\theta_A \tan\beta$, is not enhanced. However, it is also not that suppressed, which has important implications for B factories.

DETECTION OF THE NMSSM LIGHT HIGGS BOSONS

We now turn to how one can detect the h_1 and/or the a_1. At the **LHC**, all standard LHC channels for Higgs detection fail: *e.g.* $B(h_1 \to \gamma\gamma)$ is much too small because of large $B(h_1 \to a_1 a_1)$. The possible new LHC channels are as follows. <u>$WW \to h_1 \to a_1 a_1 \to 4\tau$.</u> This channel looks moderately promising but complete studies are not available. <u>$t\bar{t}h_1 \to t\bar{t}a_1 a_1 \to t\bar{t}4\tau$.</u> A study is needed. <u>$\widetilde{\chi}_2^0 \to h_1 \widetilde{\chi}_1^0$</u> with $h_1 \to a_1 a_1 \to 4\tau$. This might work given that the $\widetilde{\chi}_2^0 \to h_1 \widetilde{\chi}_1^0$ channel provides a signal in the MSSM when $h_1 \to b\bar{b}$ decays are dominant. A 4τ final state might have smaller backgrounds. Last, but definitely not least, <u>diffractive production $pp \to pph_1 \to ppX$</u> looks quite promising. The mass M_X can be reconstructed with roughly a $1-2\,\text{GeV}$ resolution, potentially revealing a Higgs peak, independent of the decay of the Higgs. The event is quiet so that the tracks from the τ's appear in a relatively clean environment, allowing track counting and associated cuts. Our [20] results are that one expects about $3-5$ clean,
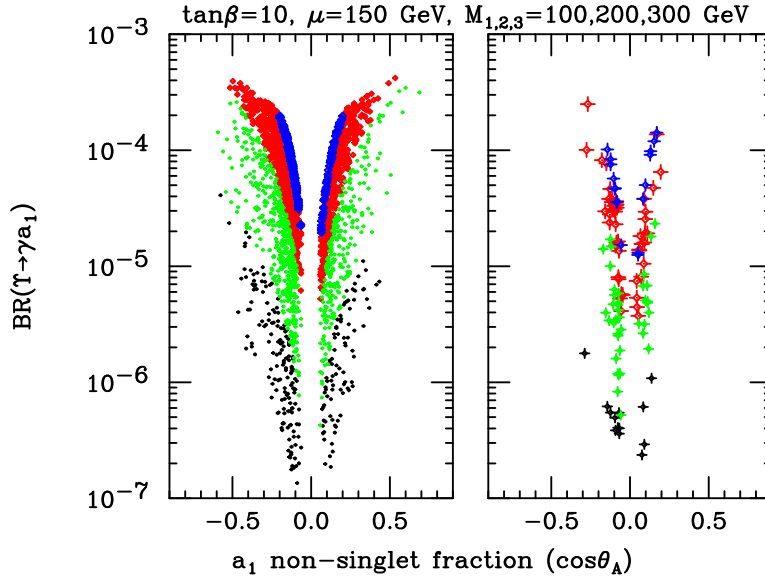
FIGURE 9. $B(\Upsilon \to \gamma a_1)$ for NMSSM scenarios. Results are plotted for various ranges of m_{a_1} using the color scheme of Fig. 8 (blue, red, green, black correspond to increasing m_{a_1} in that order). The left plot comes from an A_λ, A_κ scan, holding $\mu_{\mathrm{eff}}(m_Z) = 150$ GeV fixed. The right plot shows results for $F < 15$ scenarios with $m_{a_1} < 9.2$ GeV found in a general scan over all NMSSM parameters. The lower bound on $B(\Upsilon \to \gamma a_1)$ arises basically from the LEP requirement of $B(h_1 \to a_1 a_1) > 0.7$ which leads to the lower bound on $|\cos \theta_A|$ noted in text.

i.e. reconstructed and tagged events with no background, per 30 fb^{-1} of integrated luminosity. Thus, high integrated luminosity will be needed.

The rather singlet nature of the a_1 and its low mass, imply that direct production/detection will be challenging at the LHC. But, further thought is definitely warranted.

At the **ILC**, h_1 detection would be much more straightforward. The process $e^+ e^- \to ZX$ will reveal the $M_X \sim m_{h_1} \sim 100$ GeV peak no matter how the h_1 decays. But the ILC is decades away.

At **B factories** it may be possible to detect the a_1 via $\Upsilon \to \gamma a_1$ decays [14]. Both BaBar and CLEO have been working on dedicated searches. CLEO has placed some useful, but not (yet) terribly constraining, new limits. The predicted values of $B(\Upsilon \to \gamma a_1)$ for $F < 15$ NMSSM scenarios are shown in Fig. 9. Note that the scenarios with no light-a_1 fine-tuning are those with $|\cos \theta_A|$ close to the lower bound and m_{a_1} near to M_Υ, implying the smallest values of $B(\Upsilon \to \gamma a_1)$. Of course, as $m_{a_1} \to M_\Upsilon$ phase space for the decay causes increasingly severe suppression. And, there is the small region of $M_\Upsilon < m_{a_1} < 2m_b$ that cannot be covered by Υ decays. However, Fig. 9 suggests that if $B(\Upsilon \to \gamma a_1)$ sensitivity can be pushed down to the 10^{-7} level, one might discover the a_1. The exact level of sensitivity needed for full coverage of points with $m_{a_1} < 9.2$ GeV is $\tan \beta$-dependent, decreasing to a few times 10^{-8} for $\tan \beta = 3$ and increasing to near 10^{-6} for $\tan \beta = 50$. Discovery of the a_1 at a B factory would be very important input to the LHC program.

CAUTIONARY REMARKS

The scenario with dominant $h_1 \to a_1 a_1 \to 4\tau$ and $m_{h_1} \sim 100$ GeV certainly has many attractive properties. However, one can get quite different scenarios by decreasing the attractiveness somewhat. First, one could relax light-a_1 fine-tuning, G. While $m_{a_1} < 2m_\tau$ points have larger G values than points with $m_{a_1} > 2m_\tau$, we should be prepared for the former possibility. It yields a very difficult scenario for a hadron collider, $h_1 \to a_1 a_1 \to 4j$. Of course, a significant fraction will be charmed jets. A question is whether the $pp \to pph_1$ production mode might provide a sufficiently different signal from background in the $h_1 \to 4j$ modes that progress could be made. If the a_1 is really light, then $h_1 \to 4\mu$ could be the relevant mode. This would seem to be a highly detectable mode, so don't forget to look for it — it should be a cinch compared to 4τ. Second, we can allow more electroweak / m_Z-fine-tuning corresponding to higher F. In Fig. 6, the blue squares show that $m_{h_1} \sim 115$ GeV with m_{a_1} either below $2m_b$ or above $2m_b$ can be achieved if one accepts $F > 10$ rather than demanding the very lowest $F \sim 5$ fine-tuning measure. Of course, we do not then explain the 2.3σ LEP excess, but this is hardly mandatory. And, $m_{h_1} \sim 115$ GeV is still ok for precision electroweak. Thus, one should work on h_1 detection assuming: (a) $m_{h_1} \geq 115$ GeV with $h_1 \to a_1 a_1 \to 4\tau$; and (b) $m_{h_1} \geq 115$ GeV with $h_1 \to a_1 a_1 \to 4b$. The $pp \to pph_1$ analysis in case (a) will be very similar to that summarized earlier for $m_{h_1} \sim 100$ GeV, but production rates will be smaller. In case (b), there are several papers in the literature claiming that such a Higgs signal can be seen [21, 22] in Wh_1 production.

The most basic thing to keep in mind is that for a primary Higgs with mass $\lesssim$ 150 GeV, dominance of $h_1 \to a_1 a_1$ decays, or even $h_2 \to h_1 h_1$ decays, is a very generic feature of any model with extra Higgs fields, supersymmetric or otherwise. And, these Higgs could decay in many ways in the most general case.

Further alternatives arise if there is more than one singlet superfield. String models with SM-like matter content that have been constructed to date have many singlet superfields. One should anticipate the possibility of several, even many different Higgs-pair states being of significance in the decay of the SM-like Higgs of the model. Note that this motivates in a very general way the importance of looking for the light CP-even or CP-odd Higgs states in $\Upsilon \to \gamma X$ decays.

Another natural possibility is that the h_1 could decay to final states containing a pair of supersymmetric particles (one of which must be a state other than the LSP if $m_{h_1} < 114$ GeV). A particular case that arises in supersymmetric models, especially those with extra singlets, is $h_1 \to \widetilde{\chi}_2^0 \widetilde{\chi}_1^0$ with $\widetilde{\chi}_2^0 \to f\overline{f}\widetilde{\chi}_1^0$ — see [23, 7]. Once again, the very small $b\overline{b}$ width of a Higgs with SM-like couplings to SM particles means that this mode could easily dominate if allowed. As noted in Table 1, LEP constraints allow $m_{h_1} < 100$ GeV if this is an important decay channel. Higgs discovery would be really challenging if $h_1 \to a_1 a_1 \to 4\tau$ and $h_1 \to \widetilde{\chi}_2^0 \widetilde{\chi}_1^0 \to f\overline{f}\not{E}$ were both present.

CONCLUSIONS

The NMSSM can have small fine-tuning of all types. First, quadratic divergence fine-tuning is erased ab initio. Second, electroweak fine-tuning to get the observed value of m_Z^2 can be avoided for $m_{h_1} \sim 100$ GeV, large $B(h_1 \to a_1 a_1)$ and $m_{a_1} < 2m_b$. Light-a_1 fine-tuning to achieve $m_{a_1} < 2m_b$ and (simultaneously) large $B(h_1 \to a_1 a_1)$ (as needed above) can be avoided — $m_{a_1} > 2m_\tau$ with a_1 being mainly singlet is somewhat preferred to minimize light-a_1 fine-tuning. Thus, requiring low fine-tuning of all kinds in the NMSSM leads us to expect an h_1 with $m_{h_1} \sim 100$ GeV and SM-like couplings to SM particles but with primary decays $h_1 \to a_1 a_1 \to 4\tau$.

The consequences are significant. Higgs detection will be quite challenging at a hadron collider. Higgs detection at the ILC is easy using the missing mass $e^+ e^- \to ZX$ method of looking for a peak in M_X. Higgs detection in $\gamma\gamma \to h_1 \to a_1 a_1$ will be easy. The a_1 might be detected using dedicated $\Upsilon \to \gamma a_1$ searches. The stops and other squarks should be light. Also, the gluino and, assuming conventional mass orderings, the wino and bino should all have modest mass. As a result, although SUSY will be easily seen at the LHC, Higgs detection at the LHC will be a real challenge. Still, it now appears possible with high luminosity using doubly-diffractive $pp \to pph_1 \to pp4\tau$ events. Even if the LHC sees the $h_1 \to a_1 a_1$ signal directly, only the ILC and possibly B-factory results for $\Upsilon \to \gamma a_1$ can provide the detailed measurements needed to verify the model.

It is likely that other models in which the MSSM μ parameter is generated using additional scalar fields can achieve small fine-tuning in a manner similar to the NMSSM. However, it is always the case that low electroweak fine-tuning will require low SUSY masses which in turn typically imply $m_{h_1} \sim 100$ GeV. Then, to escape LEP limits large $B(h_1 \to a_1 a_1 + f\bar{f}\slashed{E} + \ldots)$, with most final states not decaying to b's (e.g. $m_{a_1} < 2m_b$) would be needed. In general, the a_1 might not need to be so singlet as in the NMSSM and would then have larger $B(\Upsilon \to \gamma a_1)$.

If the LHC Higgs signal is really marginal in the end, and even if not, the ability to check perturbativity of $WW \to WW$ at the LHC might prove to be very crucial to make sure that there really is a light Higgs accompanying light SUSY and that it carries most of the SM coupling strength to WW.

It is also worth noting that a light a_1 allows for a light $\tilde{\chi}_1^0$ to be responsible for dark matter of correct relic density [24]: annihilation would typically be via $\tilde{\chi}_1^0 \tilde{\chi}_1^0 \to a_1$. To check the details, properties of the a_1 and $\tilde{\chi}_1^0$ would need to be known fairly precisely. The ILC might be able to measure their properties in sufficient detail to verify that it all fits together. Also $\Upsilon \to \gamma a_1$ decay information would help tremendously.

In general, as reviewed in [7], the Higgs sector is extraordinarily sensitive to new physics from some extended model through operators of the form $H^\dagger H E$, where H is a SM or MSSM Higgs field and E is a gauge singlet combination of fields from the extended sector such a $\phi^\dagger \phi$ or $\phi + \phi^\dagger$, where ϕ is a singlet scalar field from the new physics sector. In the former case, the operator will have a dimensionless coupling coefficient and in the latter case a dimensionful coupling coefficient. This implies that in either case this new operator is likely to have large impact on Higgs decays. In the NMSSM, the supersymmetric structure implies a slightly more complex arrangement: the superpotential component $\lambda \widehat{S} \widehat{H}_u \widehat{H}_d$ and soft-SUSY-breaking term $\lambda A_\lambda S H_u H_d$ both establish a

connection between the MSSM sector and the extended singlet field sector and lead to large modifications of the light Higgs decays. Ref. [7] reviews other proposals for the extended sector. In some, E has higher dimensionality and the operator coupling coefficient is suppressed by the new physics scale but nonetheless would greatly influence Higgs physics. In general, the precision electroweak preference for a Higgs h with SM-like WW, ZZ couplings and $m_h \sim 100$ GeV greatly increases the odds that a SM-like Higgs is present but decays to new physics channels. In this context, SUSY is strongly motivated since electroweak fine-tuning is minimized precisely for $m_h \sim 100$ GeV and an extended SUSY model such as the NMSSM can provide the needed non-SM Higgs decays.

ACKNOWLEDGMENTS

REFERENCES

1. K. Riesselmann (1997), `hep-ph/9711456`.
2. C. F. Kolda, and H. Murayama, *JHEP* **07**, 035 (2000), `hep-ph/0003170`.
3. M. J. G. Veltman, *Acta Phys. Polon.* **B12**, 437 (1981).
4. Z. Y. Fang, G. Lopez Castro, J. L. Lucio, and J. Pestieau, *Mod. Phys. Lett.* **A12**, 1531–1535 (1997), `hep-ph/9612430`.
5. M. D. Scadron, R. Delbourgo, and G. Rupp, *J. Phys.* **G32**, 735–745 (2006), `hep-ph/0603196`.
6. J. R. Espinosa, and J. F. Gunion, *Phys. Rev. Lett.* **82**, 1084–1087 (1999), `hep-ph/9807275`.
7. S. Chang, R. Dermisek, J. F. Gunion, and N. Weiner (2008), `0801.4554`.
8. J. F. Gunion, and H. E. Haber, *Nucl. Phys.* **B272**, 1 (1986).
9. L.-F. Li, Y. Liu, and L. Wolfenstein, *Phys. Lett.* **B159**, 45 (1985).
10. J. F. Gunion, and H. E. Haber, *Nucl. Phys.* **B278**, 449 (1986).
11. M. Drees, *Phys. Rev.* **D71**, 115006 (2005), `hep-ph/0502075`.
12. R. Dermisek, and J. F. Gunion, *Phys. Rev.* **D77**, 015013 (2008), `0709.2269`.
13. R. Dermisek, and J. F. Gunion, *Phys. Rev.* **D76**, 095006 (2007), `0705.4387`.
14. R. Dermisek, J. F. Gunion, and B. McElrath, *Phys. Rev.* **D76**, 051105 (2007), `hep-ph/0612031`.
15. R. Dermisek, and J. F. Gunion, *AIP Conf. Proc.* **903**, 357–360 (2007), `hep-ph/0611197`.
16. R. Dermisek, and J. F. Gunion, *Phys. Rev.* **D75**, 075019 (2007), `hep-ph/0611142`.
17. R. Dermisek, and J. F. Gunion, *Phys. Rev.* **D73**, 111701 (2006), `hep-ph/0510322`.
18. R. Dermisek, and J. F. Gunion, *Phys. Rev. Lett.* **95**, 041801 (2005), `hep-ph/0502105`.
19. E. Accomando, et al. (2006), `hep-ph/0608079`.
20. J. R. Forshaw, J. F. Gunion, L. Hodgkinson, A. Papaefstathiou, and A. D. Pilkington (2007), `0712.3510`.
21. M. Carena, T. Han, G.-Y. Huang, and C. E. M. Wagner (2007), `0712.2466`.
22. K. Cheung, J. Song, and Q.-S. Yan, *Phys. Rev. Lett.* **99**, 031801 (2007), `hep-ph/0703149`.
23. S. Chang, and N. Weiner (2007), `0710.4591`.
24. J. F. Gunion, D. Hooper, and B. McElrath, *Phys. Rev.* **D73**, 015011 (2006), `hep-ph/0509024`.